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Pre-monsoon Variability of Ocean Processes along the East Coast of India

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ABSTRACT


A three-dimensional Princeton Ocean Model has been configured for the east coast of India to study the circulation and coastal upwelling during the pre-monsoon season of 2000. The model uses an orthogonal curvilinear grid and a terrain-following sigma coordinate in the vertical with monthly data fields of temperature and salinity from “Levitus94.” The model is applied to study the coastal ocean processes and its variability on weekly timescales off the east coast of India. The forcing in the model is the real-time weekly averaged wind stress obtained from Quik Scatterometer/National Center for Environmental Prediction blended wind of May 2000.

The discernable variability in the winds of May 2000 over the weekly timescale influenced the surface layers reflected in the 3-day mean satellite images. To simulate this feature and to understand the dynamics, numerical experiments are carried out with the associated real-time winds. Both diagnostic and prognostic computations are used for this, and the model simulations off Paradip and Visakhapatnam are examined to study the variability of the processes on weekly timescales. The model-simulated sea surface temperatures in different experiments are in qualitative agreement with the available 3-day mean Tropical Rainbow Measuring Mission Microwave Imager satellite images.

Apart from simulating the typical characteristic features, the model also could simulate the observed intense coastal current leaving the coast to form an eastward jet in the pre-monsoon season. The associated anomalous weaker circulation in the head bay can be attributed to the built-in opposing density currents developed within the region. The simulations suggest that the head bay is delineated from the rest of the bay in terms of its physical properties as well as physical processes.

ADDITIONAL INDEX WORDS: Bathymetry, winds, monsoons, wind-driven circulation, coastal upwelling.

INTRODUCTION

The Indian Ocean differs from the Atlantic and Pacific in its limited northward extent to only 25° N. The essential parts of the north Indian Ocean is the Arabian Sea in the west and Bay of Bengal in the east. With its unique exposure to the monsoons, it represents an area of marked seasonal variability. Although the two are bounded by nearly the same latitudes, they have very distinct basic characteristics. The Bay of Bengal has significantly low salinities because all major rivers in India discharge there and consequently is distinguished by strong near-surface stratification. The seasonally reversing winds, together with the freshwater gain during southwest monsoon and the intense air-sea interaction, particularly during the depression/cyclone development stages, make up the basic physical forcing that brings about large spatial and temporal variations of the surface waters that regulate the upper ocean circulation and the ensuing temperature and salinity fields. Differential distribution of salinity and temperature induce horizontal pressure gradients that alter the circulation. The Arabian Sea, on the other hand is an area of high evaporation that receives little freshwater from the continental land mass and hence is more saline.

The wind stress has a direct bearing on the upper layers of the ocean. It is therefore pertinent here to have an overview of the wind field, the physical processes, and circulation during the pre-monsoon and monsoon months, essentially because the wind systems are very similar right through, although the ocean circulation patterns are different. From March to May, the wind picks up strength and become more southerly. The observed coastal surface current is generated by wind forcing drives toward the north. Earlier studies by RAO, RAO, and RAJU (1986) and RAO and RAO (1989) discussed the temperature, salinity, and alongshore current structures over the inner shelf off Visakhapatnam along the east coast of India. From May, the winds begin to blow from the southwest over most of the north Indian Ocean. Over the Bay, the Ekman drift is essentially eastward. The direction remains the same from June through September, although it peaks in July. Despite the wind stress forcing being similar during pre-monsoon and monsoon months, the circulation and the thermal structures are strikingly different. Coastal ocean circulation in the Bay of Bengal during the pre-monsoon months follow the wind pattern because there is no significant freshwater flow.

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Rainfall exceeds evaporation during the monsoon and there is also freshwater influx from the river system over the Bay region. One of the unique features of the Bay of Bengal is the different regions experiencing upwelling and downwelling in different seasons along the coasts. Several workers reported this feature during the pre-monsoon. Upwelling is reported off Visakhapatnam (Murty and Varadachari, 1968) from February to May (Rao, Rao, and Raju, 1986). The surface waters in the Bay have low salinity, and stratification in the upper layers is dominated by salinity gradients (Shetye et al., 1991). Recent observations in the western Bay (Shetye et al., 1991, 1993, 1996) and the ship-drift information (Cutler and Swallow, 1984) show a distinct seasonal cycle of surface circulation. There is no evidence of upwelling north of 17° N, in spite of the locally prevailing southwesterly upwelling-favourable winds. The local absence of upwelling in the north is attributed to the southward flow of surface freshwater that would suppress the offshore Ekman transport to be expected in the sole presence of surface wind stress forcing (Johns, Rao, and Rao, 1992). Thus, the seasonally reversing monsoon winds affect the Bay of Bengal circulation significantly (Cutler and Swallow, 1984; Hastenrath and Greischar, 1989).

The semienclosed nature of the bay with an enormous quantity of freshwater discharge from the head bay river system results in a very intricate and intriguing circulation in the head bay. The available data is not adequate to understand the circulation and its variability. Hence, modelling studies are necessary to supplement and substantiate the observations. In the current study, an attempt is made to understand the intricacies involved in anomalous circulation in the northern Bay of Bengal during the pre-monsoon season. Because upwelling is a transient phenomenon on a timescale of about 4–5 days (Bowden, 1983), it is interesting to study the evolution of the processes on a weekly scale.

The oceanic circulation and the associated physical processes are quite complex and so are the modelling tools to study the same. Ocean modelling studies that use the recent modelling tools like the Princeton Ocean Model (POM), modular ocean model, S-Coordinates Rutgers University Model, Miami Isopycnic Coordinate Ocean Model, hybrid coordinate ocean model, etc., together with Levitus climatology has established that the predominant oceanographic physical processes could be realistically reproduced or simulated by these models. We have chosen POM to carry out our modelling studies.

Most of the earlier modelling studies on coastal processes for this region are confined only to climatological monthly scales. The purpose of this study is to establish the hitherto observed general oceanographic circulation features during the pre-monsoon and to extend the study further to investigate the dynamics and the associated anomalous features. An attempt is made also to ascertain the model’s potential to resolve the physical processes on the shorter timescales. Thus, the variability of the coastal circulation off the east coast of India is examined with the numerical model for May 2000 on a weekly basis and the results are validated from the available satellite observations. May 2000 is preferred because the variability is better displayed compared with other recent years for which the data is available.

**METHODOLOGY**

A three-dimensional POM has been implemented and configured on a curvilinear orthogonal grid to study the variability in circulation and coastal upwelling off the east coast of India during the month of May 2000. The numerical ocean model that is used in this study is the one described in detail by Blumberg and Mellor (1987) and Mellor (1992). It is a three-dimensional, free surface ocean model with the turbulence closure scheme of Mellor and Yamada (1982). The analysis area of the model extends from approximately 14° to 22° N of the east coast of India, covering an alongshore extent of about 750 km. The breadth of the region (distance from the coastline to the eastern open sea boundary) is about 250 km, approximately parallel to the coast as shown in Figure 1. The model incorporates a higher resolution near the coast, and in the vertical, a terrain-following sigma coordinate is used, having finer resolution near the surface and bottom and relatively coarse resolution in the middle. There are 150 (east–west) × 90 (north–south) grid points in the horizontal plane and 26 levels in the vertical, comprising 150 × 90 × 26 computational grid points. The resolution in the x direction varies from 1.3 to 3.7 km, finer near the coast and in the y direction from 11.3 to 13.8 km. The main advantage of the nonuniform grid is to use computational resources more efficiently. The time steps are based on the CFL condition, in which the two-dimensional external mode has a short time step of 12 seconds and the internal mode a longer time step of 480 seconds, depending on the associated external and internal wave speeds, respectively. An implicit numerical scheme in the vertical direction and a mode-splitting technique in time are adopted for computational efficiency. The
horizontal finite difference scheme is staggered. The boundary conditions for velocities include radiation conditions at the open boundaries.

After the model parameters like the domain, grid, and bathymetry are set, the model is initialized with a cold start (assuming the velocity field to be zero at the start) using climatological values of temperature and salinity from databases. We obtain monthly data fields of temperature and salinity as initial density fields derived from “Levitus94: World Ocean Atlas 1994.” The real-time weekly averaged wind of May 2000 is obtained from the National Center for Environmental Prediction (NCEP), which is blended with a NASA Quik Scatterometer (QuikScat) cantered on the analysis time and is referred to as QuikScat/NCEP blended ocean winds with a spatial resolution of 0.5 × 0.5 degrees. The wind data is available from July 1999 at http://dss.ucar.edu/datasets/ds744.4. The data is qualitatively in good agreement with the real-time scatterometer wind from Quikscat. The data are available on a 6-hour basis, which is averaged over a week. The model uses the bottom topography derived from the ETOP05 (Earth Topography Five-Minute) from the NGDC database as shown in Figure 1. A bilinear interpolation has been used to obtain all the input data (i.e., temperature, salinity, winds, and bathymetry) at computational grid points. The smoothed topographic gradients are used by the model which could have otherwise caused spurious along-slope currents in a sigma coordinate model (Haney, 1991). A mathematical tool SEAGRID (http://woodshole.er.usgs.gov/staffpages/cdenham/public. html/seagrid/seagrid.html) for MATLAB is used to convert the rectangular grid to an orthogonal curvilinear grid, which also enhances model resolution at the selected regions. The model is then integrated with the use of wind stress forcing to capture the transient coastal upwelling feature, which is validated with the available sea surface temperature (SST) satellite images.

After the model parameters of temperature and salinity (density) are also set as starting values, we need to have the starting values for sea level and velocity as well. To accomplish this, the model was spun up with constant forcing, keeping the temperature and salinity constant until it reached steady state. This means that the model ocean is initialized with the present ocean state and is integrated forward until the circulation is consistent with the prescribed water mass structure. In other words, it adjusts geostrophically to its initial state. It is usually difficult for basin-scale and global general circulation models to reach this state because it can take years to reach this so called quasi-geostrophic state. However, if one is concerned only with the wind-driven flows, including that arising from sea surface slopes resulting from Ekman pumping, a spin-up time of the order of days could be adequate (http://ioc.unesco.org/oceanteacher/OceanTeacher2/ other/NOMModeling/modeling/initial.html).

**NUMERICAL EXPERIMENTS**

Numerical experiments involve the use of both diagnostic and prognostic modes. In the prognostic mode, the momentum equations as well as equations governing the temperature and salinity distributions are integrated as an initial value problem. These predictive experiments do not always reach a steady state because the oceanic response time for the density field can be considerable.

The experiments in the diagnostic mode attain steady-state conditions after about 10–15 days. The diagnostic approach not only provides a powerful tool for deducing circulation but also permits a consistent way of initializing a prognostic mode. The above-configured east coast model’s performance is demonstrated in simulating the variability in the circulation and the associated processes during the pre-monsoon season.

Figure 2 depicts the initial horizontal temperature from the Levitus climatology for the month of May and Figure 3a–d the mean weekly wind for the 4 weeks of May 2000. Although the winds in all four cases are essentially from the southwest and are spatially uniform, the first week winds have more of a southerly component than the rest. The third and fourth week winds are more aligned to the coast and are more southwesterly. The second week winds are the weakest (2–5 m/s) of all, and the fourth week winds are the strongest (>10 m/s). It should be noted that the initial density field used in the model is that of the previous month (April) with reference to the wind field (May) considered for model integration. The salinity field is not shown here because discernible variations are found only during the monsoon period. Figure 4a–d shows the simulated surface horizontal current corresponding to the 4 weeks after the prognostic computations.

The common conspicuous feature in all the 4-week simulated circulations is that the strong western boundary current near 19° N takes off from the coast. This leaves the western boundary current considerably weak north of Gopalpur, elusive to the conventional and classical Ekman dynamics because winds are rather uniform spatially. However, to affirm the same, the wind field is analysed and the Ekman transport examined for any significant variation along the

![Figure 2](image-url)
coast to cause this anticyclonic tendency. The Ekman transport, \( M_e \), can be computed as \( M_e = \tau f \). Here, \( M_e \) is the wind-generated mass transport per unit width integrated over the depth of the Ekman layer (kg m\(^{-1}\) s\(^{-1}\)); \( \tau \) is wind stress, and \( f \) is the Coriolis parameter. Figure 5a–d denotes the contours of Ekman transport for all the 4 weeks of May 2000. It can be seen that the contours of the third and fourth week (Figure 5c, 5d) are meridional and do not signify much variation along the coast. The first week contours (Figure 5a), however, show that the Ekman transport is at its maximum (1600 kg m\(^{-1}\) s\(^{-1}\)) near and south of Paradip. The second week Ekman transport (Figure 5b) is considerably weak (<800 kg m\(^{-1}\) s\(^{-1}\)) all along, and particularly feeble off Paradip. Thus, one can decipher that the distribution of the wind stress forcing (or mass transport) along the coastline cannot beget the anomalous jet near Gopalpur.

To investigate further, the diagnostic computations have been examined to understand and corroborate this novel feature. In the diagnostic calculations, it might be relevant here to reiterate that the temperature and salinity fields are fixed and are equal to the Levitus monthly fields for April. The vertically integrated density-driven circulation is shown in
Figure 4. Model-simulated surface current for May 2000 in (a) first week, (b) second week, (c) third week, and (d) fourth week showing anticyclonic gyre (ACG) and cyclonic eddy (CE).

Figure 6. Also, these are the common initial conditions to the prognostic model integration for all the 4-week model simulations. Although it is noisy, it is interesting to note a relatively broad southward current in the northern region along the coastline. This implies that the temperature-salinity structure is such that it would produce the southward flowing, density-driven steering current in the absence of external (wind stress) forcing. This inbuilt hydrodynamic latent opposing force, in balance with the density field, could be hampering the development of the western boundary current, the so-called East India Coastal Current, in the prognostic calculations that follow. This observed uncharacteristic feature is evident from the analysis of the hydrographic data (BABU et al., 2003), as shown in Figure 7. According to the authors (p. 860),

The northward flow in the west, termed as the Western Bay of Bengal Current (WBBC), is conspicuous with
large horizontal gradients. The dynamic topography also shows that WBBC meander at 14° N, reaching the shelf north of 16° N. Further, it continues northward as an intense coastal current up to 17.5° N, where it leaves the coast to form a strong eastward jet between CE2 and ACG.

The features of ACG and CE2 in the above context can be assumed to correspond to the two anticyclonic and cyclonic tendencies shown in Figure 4d. Thus, we can conclude that the head bay region is very typical yet unique by itself in the sense that not only the seasonally reversing surface winds but the discharges from the head bay river system induce surface and subsurface currents to undergo periodic reversals, resulting in an intricate dynamic balance between the barotropic and the ensuing baroclinic forcings in typical time-scales. This indicates that numerous other processes and features of the head bay circulation need to be further explored.

To investigate the bearing of the initial conditions, instead of April Levitus monthly climatology, February initial temperature and salinity are used. The model-simulated surface current with fourth week (May) winds is shown in Figure 8. This circulation does not show the ambiguous anticyclonic gyre
near the Gopalpur region. Thus, the observed anomalous feature (Babu et al., 2003) might therefore be assumed to be caused by the initial density field.

To continue and complete the discussion of the model simulations of May, the current strengths are in accordance with the overlaying wind field. The western boundary current between Machilipatnam and Gopalpur is weakest (~40 cm/s) in the second week and strongest in the fourth week (>60 cm/s). Figures 9a–d and 10a–d show the horizontal temperature and sea surface elevation simulated by the model as a response to pure wind stress forcing in May for the corresponding 4 weeks. It should be noticed that the coastal waters are cooled up to 19.5°C, with an emphasis between Visakhapatnam and Gopalpur. According to the observations available for the pre-monsoon, it is well documented that the coastal waters off Visakhapatnam are cooled because of upwelling-favourable winds. However, we do not have sufficient documentary evidence of the same for Paradip. The model-simulated sea surface elevation is consistent with the horizontal temperature distribution. It can be noted here that the upwelling is associated with the lowering of sea level, following the offshore Ekman transport at the coast. Hence, we can ascertain that the model is able to simulate the upwelling processes in this region reasonably well. To investigate the upwelling processes in detail, the vertical cross sections of two stations—one in the south (Visakhapatnam) and another in the north (Paradip)—are examined. Figure 11a, 11b depicts the initial vertical cross-shelf section of temperature off Visakhapatnam and Paradip, respectively, for the month of April, which is the initial temperature field common to all four cases. This shows a surface coastal temperature of about 28.5°C up to a depth of about 10 m at Visakhapatnam. The surface coastal SST is colder at Paradip at 28.0°C. The model-simulated vertical thermal structure off Visakhapatnam and Paradip are shown Figures 12a–d and 13a–d, respectively. The model-simulated results are tabulated in Table 1.

The coastal upwelling activity is seen in terms of reduction of SST near the coast. The evolution of the coastal upwelling processes from coastal circulation, taking place along the coast off Paradip and Visakhapatnam, is discussed here. The SST from the weekly simulations off Visakhapatnam and Paradip show that the temperature drop is minimal during the second week and maximal during the fourth week. It is interesting to note that the temperature difference at Paradip is consistently 0.5°C lower (compared with Visakhapatnam) in any particular week. The upwarping tendency is seen throughout the 200-m depth, shown in the Figures 12 and 13.
in the case of Visakhapatnam, whereas a clear upwarping tendency is seen at Paradip only in the fourth week at up to 50 m depth. Further discussion of the model-simulated results for the two stations on a weekly basis, with special reference to upwelling, is presented below.

First Week
The maximum sea surface temperature near the coast at Visakhapatnam is reduced to nearly 27.5°C from its initial value of about 28.5°C, indicating a temperature drop of about 1.0°C. The 27.5°C isotherm just reaches to the sea surface from below 25 m depth, forcing the 29.0°C isotherm to migrate away.

The initial near-coast surface temperature at Paradip is about 27.5°C. On comparison, it is found that the computed sea surface temperature is cooled by only 0.5°C from its initial value. However, it should be very carefully noted that although the upwelling feature is not exhibited here at Par-
Second Week

The maximum sea surface temperature near the coast at Visakhapatnam is reduced to 28.0°C from its initial value of about 28.5°C, indicating a temperature drop of about 0.5°C. The 28.0°C isotherm outcrops to the sea surface from below 20 m depth.

Third Week

The initial near-coast surface temperature at Paradip is about 28.0°C, indicating no change in temperature.

The vertical temperature structure and the upwelling features are nearly same as in the first week, both at Visakhapatnam and Paradip. However, as the horizontal surface temperature fields (Figure 9) show, the upwelling processes reach just south of Paradip in the third week, whereas it is prevalent only up to Gopalpur in the third week.
Fourth Week

The upwelling processes are displayed most during this week, both at Visakhapatnam and Paradip. The maximum sea surface temperature near the coast at Visakhapatnam is reduced to 26.5°C from its initial value of about 28.5°C, indicating a temperature drop of more than 2°C. The 26.5°C isotherm outcrops to the sea surface from about 50 m depth.

The computed sea surface temperature near the coast at Paradip is 26.5°C, showing a surface cooling of 1.5°C from its initial value of 28.0°C.

Validation of the Model-Simulated Results with TMI Satellite Images

The model-simulated thermal fields are validated with 3-day mean total Tropical Rainfall Measuring Mission Microwave Imager (TMI) SST images. These 3-day mean satellite images can be obtained from the web site (http://www.remss.com/tmi/tmi_3day.html). The reason to choose this duration is that it is the minimum time required to get the best SST images. These 3-day mean SST images can be assumed to represent the transient nature of coastal upwelling. The model-computed thermal fields off Paradip and Vi-

<table>
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<th>Week</th>
<th>Visakhapatnam</th>
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<td></td>
<td>Initial</td>
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<tr>
<td>1</td>
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Figure 11. Initial vertical temperature (°C) at (a) Visakhapatnam and (b) Paradip for May 2000.

Figure 12. Model-simulated vertical temperature (°C) off Visakhapatnam for May 2000 in (a) first week, (b) second week, (c) third week, and (d) fourth week.

Figure 13. Model-simulated vertical temperature (°C) off Paradip for May 2000 in (a) first week, (b) second week, (c) third week, and (d) fourth week.
Sakhaptnam have been validated with the available respective weeks of TMI SST images. According to the temperature colour bar of the image, the dark red colour indicates prevalence of high temperatures, and a more yellow colour means relatively low temperatures. Hence, coastal upwelling is relatively less in the red-coloured region and more in the yellow-coloured zone. Figure 14a–d depicts the 3-day mean sea surface temperatures ending 6 May, 13 May, 22 May, and 25 May, representing the 4 weeks of May 2000, respectively. It can be easily seen from the colour bar that the second week is warmest and the fourth week is coldest among the four. A careful examination of Figure 14a and 14c indicates that the region between Paradip and Visakhapatnam is cooler in the first week compared with the third week, whereas the region south of Visakhapatnam is nearly the same in both cases. Thus, the model-simulated thermal field that supports the upwelling process agrees qualitatively with the available satellite images and shows that the model could capture and resolve the transient coastal upwelling features on a weekly timescale.

**CONCLUSIONS**

Although many studies on coastal upwelling processes have been made on a monthly scale, it is perhaps for the first time an attempt has been made to look into the variability of the processes on a weekly scale. The semienclosed nature of the bay with an enormous quantity of freshwater discharge from the head bay river system results in a very intricate and intriguing circulation in the head bay. The western boundary current during the pre-monsoon season near 19°N takes off from the coast, leaving the western boundary current considerably weak north of Gopalpur, elusive to the conventional and classical Ekman dynamics because winds are rather spatially uniform. We can conclude that the head bay region is very typical yet unique in the sense that not only
the seasonally reversing surface winds, but also the discharges from the head bay river system, induce surface and subsurface currents to undergo periodic reversals, resulting in an intricate dynamic balance between the barotropic and the ensuing baroclinic forcings in typical timescales. This implies that numerous other process and features of the head bay circulation need to be further explored.

**LITERATURE CITED**


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Figure 14 from “Pre-monsoon Variability of Ocean Processes along the East Coast of India” by S.V. Babu, A.D. Rao, and D.K. Mahapatra, pp. 628-639. Three-day TMI satellite images.

Figure 5 from “Mapping Migratory Wading Bird Feeding Habitats using Satellite Imagery and Field Data, Eighty-Mile Beach, Western Australia” by Suzanne Wade and Robert Hickey, pp. 759-770. Chart showing the median grain size at each sample site (occurrence) per spectral category, thus illustrating the relationship between spectral category and grain size (for example, categories 16 and 17 are dominantly very fine-grained sediments).

Figure 7 from “Mapping Migratory Wading Bird Feeding Habitats using Satellite Imagery and Field Data, Eighty-Mile Beach, Western Australia” by Suzanne Wade and Robert Hickey, pp. 759-770. Chart showing the frequency of occurrence of selected benthic invertebrates at each sample site (occurrence) per spectral category, thus illustrating the relationship between spectral category and benthic invertebrates (for example, Siliqua pulchella dominates spectral categories 9, 10, and 15, but is rare or not present elsewhere).